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(12) UK Patent Application (19) GB (11) 2 167 253 A

(43) Application published 21 May 1986

(21) Application No 8527959

(22) Date of filing 13 Nov 1985

(30) Priority data
    (31) 671156   (32) 13 Nov 1984   (33) US

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(51) INT CL⁴
    H02P 6/00

(52) Domestic classification
    H2J 12P 14D BM

(56) Documents cited
    US 4270075

(58) Field of search
    H2J
    Selected US specifications from IPC sub-class H02P

(54) **Method and apparatus for noise-quieting in brushless DC motors**

(57) A circuit for driving a brushless DC motor which reduces the interaction of axial forces between the motor windings (W_1, W_2) and the permanent magnet rotor. The circuit provides feedback of the back EMF developed by the motor winding (W_2) from which power is being removed to the motor winding (W_1) to which power is being applied.
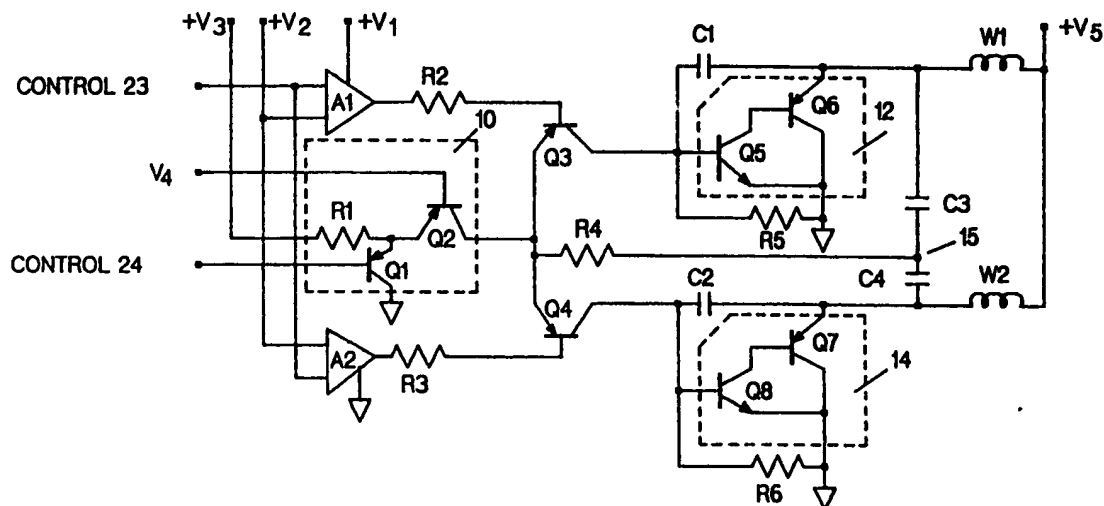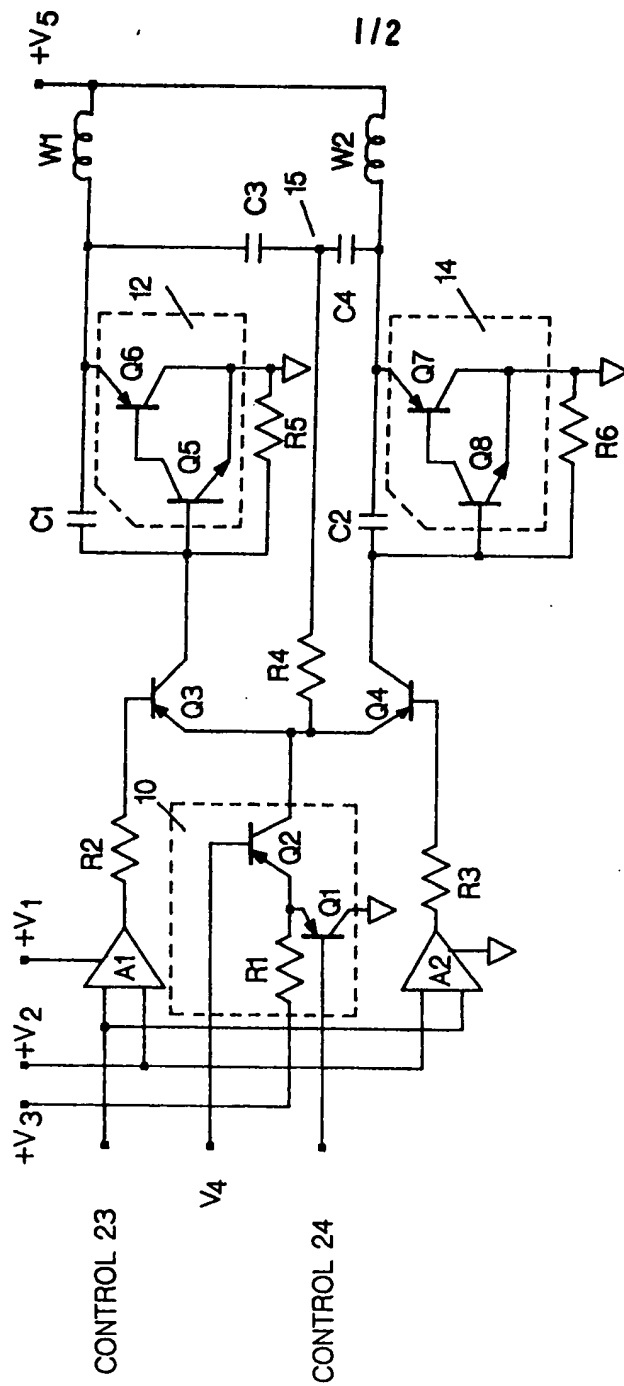
FIGURE 1
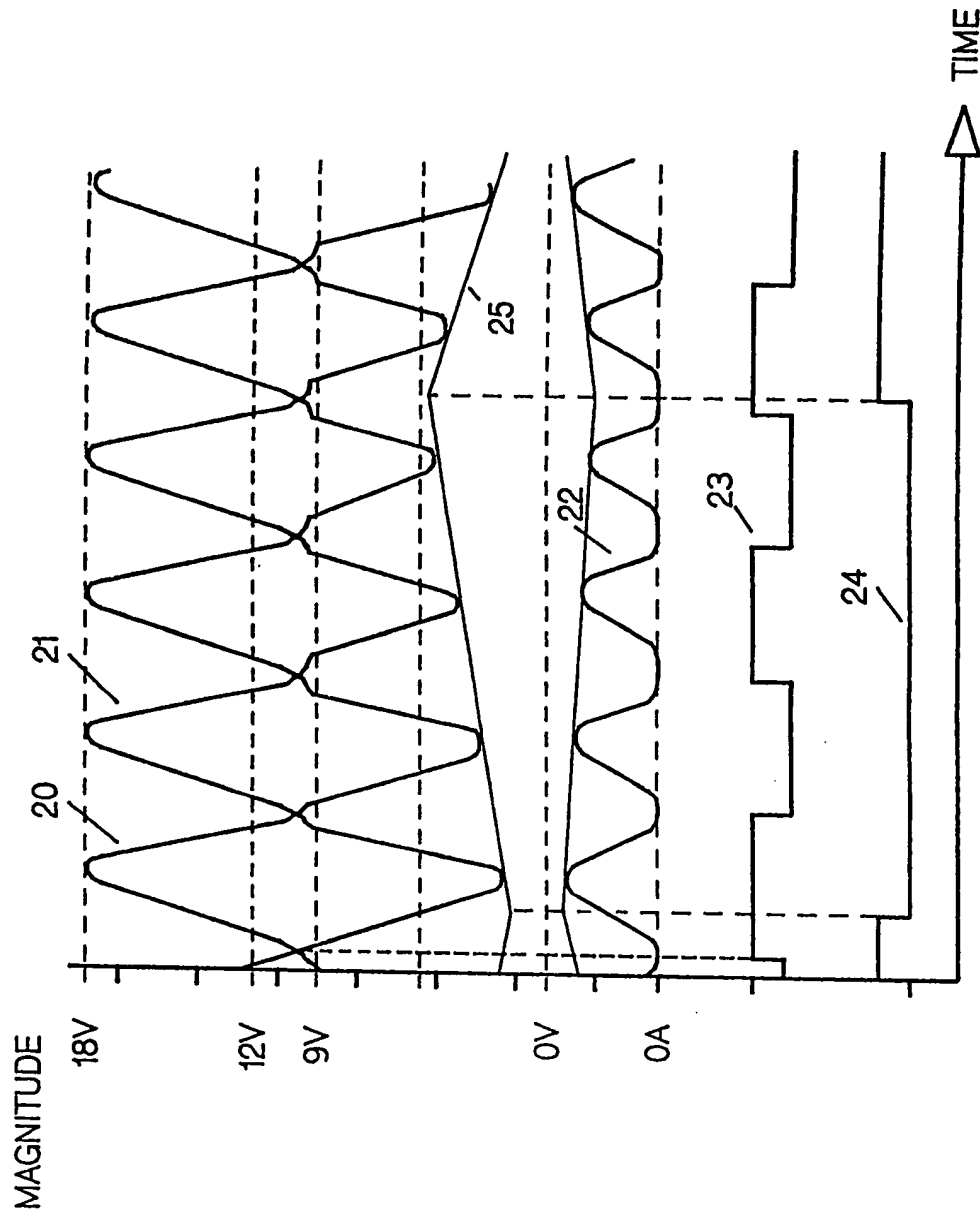
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FIGURE 1

FIGURE 2

SPECIFICATION

Method and apparatus for noise-quieting in brushless DC motors

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The present invention relates to electronic circuitry for driving brushless DC motors. In particular, this invention provides a method and circuitry for quieting audio frequency noise
10 produced by such motors when driven by conventional circuit configurations.

At least one source of audio frequency noise produced by brushless DC motors is caused by the interaction of forces set up be-
15 tween the motor windings and the permanent magnet rotor when driven by conventional circuitry. Typically, convention circuitry comprises power transistors which alternately draw current through the motor windings from
20 a power supply on demand derived from a signal produced by a Hall effect device as the rotor rotates. This scheme simply draws required current through the windings to control motor speed.
25 According to one aspect of the present invention, there is provided apparatus for driving a brushless DC motor having a plurality of windings, said apparatus comprising driver means for sequentially applying drive current
30 to the windings of the motor; and feedback means, coupled to the driver means, for applying the back EMF developed by the motor winding from which drive current is being removed to the motor winding to which drive
35 current is being applied.

According to another aspect of the present invention, there is provided a method for driving a brushless DC motor having a plurality of windings, said method comprising the steps
40 of alternately applying drive current to the windings of the motor; and applying the back EMF developed by the motor winding from which drive current is being removed to the motor winding to which drive current is being
45 applied.

In the accompanying drawings:–
Figure 1 is a schematic diagram of the motor driver constructed according to the principles of the present invention; and
50 Figure 2 is a timing diagram of control and drive signals for the motor driver circuit of Fig. 1.

The spindle motor driver circuit of Fig. 1 energizes motor windings W_1 and W_2 in re-
55 sponse to signals produced by a Hall effect device and a microprocessor. More particularly, a first cyclic control waveform 23 determines which winding W_1 or W_2 is energized on the basis of the rotational position of the
60 rotor as sensed by the Hall effect device (not shown); a second cyclic control waveform 24, of lower frequency than the control waveform 23, is used to slowly increase and decrease the average level of energization of the wind-
65 ings W_1 and W_2 in order to assist stability of

the motor speed. Both control waveforms 23,24 are generated by a controlling microprocessor (not shown).

A current source 10 comprises Q_1, Q_2 and
70 R_1. The base of Q_2 is coupled to reference voltage V_4 and the base of Q_1 is connected to control signal 24. The emitters of transistors Q_1 and Q_2 are commonly coupled to reference voltage V_3 through resistor R_1.
75 Referring to Fig. 2, when control signal 24 is high Q_1 is off (i.e. cut off) and Q_2 is on (i.e. active). The voltage at the emitters of Q_1 and Q_2 is approximately 4 volts. In the present example, approximately 4.2 milliamps of cur-
80 rent is available from the collector of Q_2.

When control signal 24 is low Q_1 is turned on as current flows from its base. As current flows through R_1, Q_2 becomes back-biased and is turned off.
85 The motor winding to which power is supplied is selected by comparators A_1 and A_2. When control signal 23 is low, motor winding W_1 is selected by comparator A_1. Conversely, motor winding W_2 is selected by comparator
90 A_2 when control signal 23 is high.

Transistor Q_3 functions as a switch when the output of comparator A_1 is low. Base current drawn through R_2 causes Q_3 to saturate thus providing short circuit from its emitter to
95 collector. Transistor Q_4 functions in the same manner in response to low voltage at the output of comparator A_2.

Transistors Q_5 and Q_6 operate as Darlington pair 12 to provide power to motor winding
100 W_1. Thus substantial drive current can be provided in response to minimal control current applied to the base of Q_6. Capacitors C_1 and C_3 and resistor R_5 are used to control the rate at which power is applied to the motor wind-
105 ings and to provide feedback of back EMF produced by de-energized motor winding W_2 for reducing audio frequency noise. An identical circuit comprising Darlington pair 14 (i.e. transistors Q_7 and Q_8), capacitors C_2, C_4 and
110 resistor R_6 is provided to drive motor winding W_2.

Referring again to Fig. 2, waveforms 20 and 21 respectively represent the voltage drive waveforms for the windings W_1 and W_2
115 (these voltages being those present at the node between winding W_1 and capacitor C_3 and at the node between winding W_2 and capacitor C_4 respectively).

When control signal 24 is low, current
120 source 10 is off. Assuming motor winding W_2 was energized just prior to control signal 24 changing from high to low state, minimum operating charge still exists in capacitor C_4. If control signal 23 is high so that comparator
125 A_2 has caused Q_4 to turn on, capacitor C_4 then charges through resistor R_4 to the base of transistor Q_8. As capacitor C_4 charges toward the voltage level V_5, Darlington pair 14 is turned on and current flows in resistor R_6.
130 Thus, the voltage at circuit node 15 is fixed at

approximately 1 volt. Feedback from C_4 assures that the voltage remains fixed as long as Darlington pair 14 is not saturated.

The rate at which C_4 charges, and conse-
5 quently the rate at which the energization of winding W_2 is reduced over several switching cycles, is substantially determined by the current flowing through R_6. The current into the base of Q_8 and into C_2 is negligible because of
10 the high gain of Darlington pair 14.

If C_4 charged faster, the current flowing to ground through resistor R_6 would increase the base voltage of Q_8 thus turning it on more. If Q_8 is turned on harder, more power is applied
15 to motor winding W_2 which increases the voltage drop across W_2 and forces the voltage at circuit node 15 to decrease. If the voltage at that node decreases, current through R_6 decreases, which in turn reduces the base vol-
20 tage of Q_8.

With continuing reference to Figs. 1 and 2, when control signal 24 is high, current source 10 is turned on. If control signal 23 is also high, more power is applied to the motor
25 winding at a rate primarily determined by the rate determined by C_4 discharging through R_4. Thus, the current from current source 10 is divided through resistor R_6, on the one hand, and R_4 on the other. The amount of current
30 flowing through R_6 is determined by V_{be} of Q_8 divided by R_6. The balance of the current available from current source 10 charges capacitor C_4 through resistor R_4. At this time, the voltage at the C_4 R_4 node 15 is fixed at
35 approximately 0.3 volts. By making the voltage at circuit node 15 different when power is applied to winding W_2 than when power is removed from winding W_2, the stability of motor speed is enhanced.
40 Capacitors C_3 and C_4 allow coupling from the winding which the circuit is not driving to the winding which the circuit is driving by fixing the voltage at circuit node 15. The back EMF generated in the winding not being driven
45 is inverted and applied to the winding which is being driven during the middle of each phase of control signal 23. See for example, motor drive voltage 21 driving window W_2 during positive phase of control signal 23 shown in
50 Fig. 2. Approximately 6 volts of back EMF is being added to motor winding W_2 from motor winding W_1 during the first full, positive phase of control signal 23.

Capacitors C_1 and C_2 control the rate at
55 which power is switched between motor windings W_1 and W_2 (C_1, C_2 are much smaller in value than C_3, C_4). For example, when transistor Q_4 turns off and transistor Q_3 turns on in response to control signal 23 changing
60 state, the Darlington pair 14 turns off at a rate determined by the discharge of capacitor C_2 through R_6. Thus, as voltage 21 rises, motor drive voltage 20 decreases at the same rate because capacitor C_4 provides coupling to
65 circuit node 15. Thus, the voltage being re-

moved from motor winding W_2 is transferred to motor winding W_1 in a relatively short period of time. Capacitors C_1 and C_2 also protect transistors Q_6 and Q_7 from voltage breakdown
70 owing to high transient voltages produced by motor windings W_1 and W_2 if drive current 22 were reduced too rapidly when power is switched from one winding to the other.

Referring again to Fig. 2, drive current 22 is
75 applied to motor winding in phase with drive voltages 20 and 21. Thus, current is switched from one motor winding to the other approximately coincident with a change of state of control signal 23.
80 As stated elsewhere in this specification, when control signal 24 is high, current source 10 provides current to transistors Q_3 and Q_4. Control signal 23 determines which path the current shall take. When control signal 23 is
85 high, current flows through Q_4; when control signal 23 is low, current flows through Q_3.

The source of control signal 23 is a Hall effect device which monitors the magnetic field of the rotor of the motor being driven to de-
90 termine the appropriate winding to which power should be applied.

When control signal 23 is high and control signal 24 is low, current source 10 is turned off. When control signal 23 is high, Q_4 effec-
95 tively connects capacitor C_4 to the base of transistor Q_8 via resistor R_4. Since no current is supplied by current source 10, Darlington pair 14 is turned off at a rate determined by the charging of capacitor C_4 through resistor
100 R_6. The base current required by transistor Q_8 and the charging current of capacitor C_2 has negligible effect on the turn off rate of Darlington pair 14.

Capacitors C_3 and C_4 integrate current from
105 current source 10 between the rapid phase transitions of control signal 24 to a slowly varying drive level 25 at the motor winding being driven. Thus, when control signal 24 is low, voltage drive level 25 linearly decreases;
110 when control signal 24 is high, voltage drive level 25 linearly decreases and increases in phase with voltage drive level 25. It should be noted that voltage drive level 25 decreases as the negative magnitude of voltage 20 and 21
115 decreases.

The rate of integration by capacitors C_3 and C_4 is controlled by the current flowing through resistor R_4 which current is the difference between the current from current source 10 and
120 the current flowing through resistor R_5 or R_6. Current flows from current source 10 when control signal 24 is high. Thus, the voltage on capacitors C_3 or C_4 charges at a rate determined by the current through resistor R_4.
125 Since the voltage at circuit node 15 is fixed by feedback from Darlington pair 12 or 14, voltage drive level 25 varies linearly with integration of the current flowing through resistor R_4. When control signal 24 is low, no current
130 flows from current source 10 and the current

through resistor R₄ is equal to the current in resistor R₅ or R₆.

Resistor R₄ helps stabilize the speed control loop by providing an immediate increase or
5 decrease of the voltage at circuit node 15 as necessary to maintain constant level. The amount of such increase or decrease is determined by the difference between the current flowing through resistor R₄ from current
10 source 10 in response to control signal 24 when it is high, and the current flowing through resistor R₄ to ground via resistor R₅ or resistor R₆ when control signal 24 is low.

Under ordinary load conditions, the drive
15 current 22 of Fig. 2, effectively turns off at or near transitions of control signal 23. Since interaction of forces between the motor windings and the permanent magnet rotor are greatest during those transitions while is flow-
20 ing in the motor windings, decreasing drive current 22 near such transitions substantially reduces those interacting forces and the resultant audio frequency noise.

When current is flowing in one motor wind-
25 ing at a transition of control signal 23, capacitor C₁ or C₂ controls the rate at which drive voltage is transferred to the other winding. In addition, by controlling the rate of turn off of the drive voltage, capacitor C₁ or C₂ prevents
30 voltage breakdown of its respective Darling pair caused by the inductance of the motor winding. Thus, when transistor Q₄ turns off and transistor Q₃ turns on, Darlington pair 14 turns off at a rate determined by the dis-
35 charge of capacitor C₂ through R₆.

In addition to ensuring stability of the speed regulation loop, R₄ regulates the flow of current from capacitors C₃ and C₄ which have been excessively charged during start up. Dur-
40 ing start up, power transistors Q₆ and Q₇ saturate, which drives circuit node 15 positive. Resistor R₄ maintains saturation of the power transistor which is applying power to a motor winding when the induced voltage, developed
45 by the winding from which power is being removed, begins to decrease. Thus, resistor R₄ limits the discharge of capacitors C₃ and C₄ to assure effective start up of the motor.

50 CLAIMS
1. Apparatus for driving a brushless DC motor having a plurality of windings, said apparatus comprising:
driver means for sequentially applying drive
55 current to the windings of the motor; and
feedback means, coupled to the driver means, for applying the back EMF developed by the motor winding from which drive current is being removed to the motor winding to
60 which drive current is being applied.
2. A method for driving a brushless DC motor having a plurality of windings, said method comprising the steps of:
alternately applying drive current to the
65 windings of the motor; and

applying the back EMF developed by the motor winding from which drive current is being removed to the motor winding to which drive current is being applied.
70 3. Apparatus for driving a brushless DC motor, said apparatus being substantially as hereinbefore described with reference to the accompanying drawings.
4. A method of driving a brushless DC
75 motor, said method being substantially as hereinbefore described with reference to the accompanying drawing.